UNDERSTANDING THE RESPONSE OF COMMON SPACECRAFT SHIELDS TO HYPERVELOCITY IMPACTS OF METEORITE AND OTHER TERRESTRIAL ANALOG MATERIALS. C. J. Cline II[1], E. L. Christiansen[1], R. McCandless[2], J. Miller[3], B. A. Davis[2], J. Resendez[2]. [1]NASA Johnson Space Center, Astromaterials Research and Exploration Science, Mail code XI5, 2101 NASA Parkway Houston, TX 77058 (christopher.j.cline@nasa.gov). [2]Jacobs Technology, NASA Johnson Space Center, Astromaterials Research and Exploration Science, Mail code X15, 2101 NASA Parkway Houston, TX 77058. [3]University of Texas at El Paso, El Paso, TX 79968, United States.

Introduction: Micrometeoroid and orbital debris (MMOD) populations can vary significantly in composition, density, and homogeneity. Hypervelocity testing campaigns intended to design and optimize MMOD shields for spacecraft are recognizing the need to investigate shield response from different types of impactors that span the range of densities observed in the MMOD population, such as nylon, Al, Al_2O_3, steel, and Cu [1,2]. These tests, however, still predominantly employ spherical and homogenous projectiles. Adding any compositional or mineralogical complexity to the impactor, such as what would be expected from a polymineralic micrometeoroid, for example, will be concomitant with a more complex shockwave structure in the projectile after it impacts the outer surface of any type of MMOD shield. The magnitude of these complexities will depend on how varied the mineralogy of the projectile is, but in the case of a metal-bearing chondrite, the disparate shock impendence between adjacent metal and silicate grains will potentially create localized areas of shock focusing (local increase in nominal shock pressure), or shock shadowing (local decrease in nominal shock pressure).

The response of a MMOD shield is generally predicted using a ballistic limit equation – a semiempirical curve, derived from hypervelocity testing data, that denotes a particle diameter (for a given set of impact conditions such as projectile density and impact angle) when a shield will fail as a function of impact speed. These curves exhibit inflection points as a function of impact speed that represent when the projectile experiences sufficient pressure to fragment, melt, or vaporize. The introduction of shock focusing and shadowing in a heterogenous projectile will add uncertainty to the predicted pressures needed to go through each transition, leading to increased uncertainty in the expected performance of the MMOD shield. Therefore, it is necessary to explore the performance of MMOD shields in hypervelocity tests against more complex, natural projectile materials. To this end we have conducted a comparative test series to begin investigating the impact damage caused by meteoritic and terrestrial-analog projectiles, to that of spherical Al projectiles of similar mass.

Methods: A total of five impactor types were used in this study, an ordinary chondrite, dunite, basalt, telluric Fe, and Al for a baseline test. The meteorite sample used was a 3.3 mm thick-section of NWA 10731, an L3-6 ordinary chondrite containing abundant chondrules, and notable inclusions of troilite and FeS. Concern existed over the ability to successfully launch this relatively coarse-grained, low-strength, meteorite fragment, so three other terrestrial analogs were also selected as projectile materials. Dunite and basalt were chosen for their ubiquity in impact modeling at a variety of spatial scales, in combination with the availability of robust equations-of-state. The fourth material was a Tertiary basalt from Disko Island, Greenland, that contains blebs of high-carbon Fe and Fe_3C [3,4] and is a

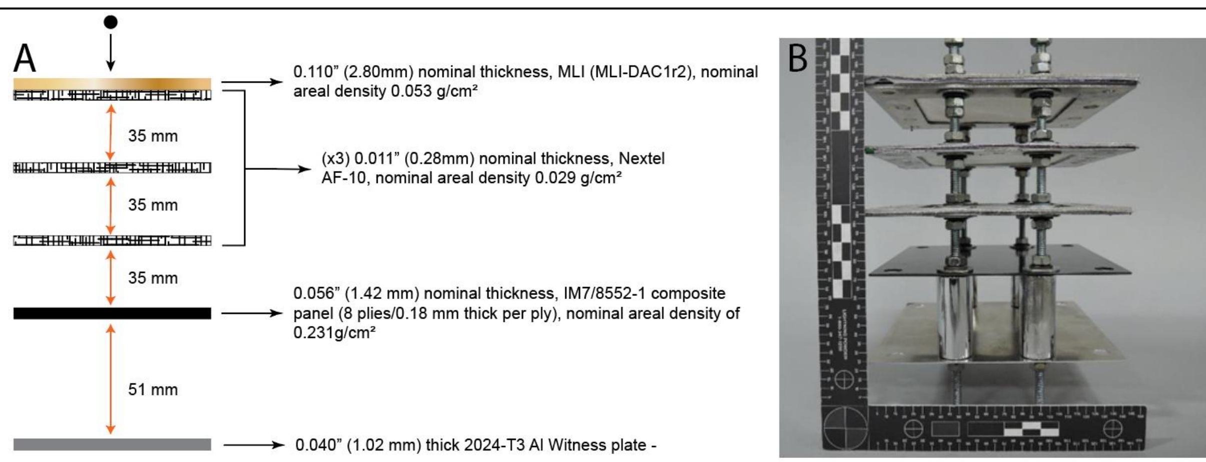

Figure 1. (A) Schematic (A) and (B) picture of shield layup used for all reported testing.

good physical analog to the meteorite in regard to it being a pre-dominantly lithic matrix that contains Fe-rich metallic inclusions. All meteoritic/lithic projectiles were fabricated into cylinders with a length:diameter ratio as close to unity as practical, with the meteorite having a larger ~3 mm length, and the other lithics being ~2 mm. The two comparative Al projectiles tests used 3.3 and 2.2 mm spheres that had similar mass to either the meteorite or average of the rock projectiles.

Eight successful hypervelocity tests were completed at the Remote Hypervelocity Test Laboratory at NASA White Sands Test Facility using a .17 caliber two-stage light-gas gun. This included one meteorite and basalt cylinder, two dunite and telluric iron cylinders, and two Al spheres. Impact speeds varied between 5.66 and 7.06 km s^{-1} depending on the projectile type, and tilt of the cylindrical axis was measured using two high-speed cameras oriented 90° apart in a plane normal to the projectile trajectory.

The shield design used in all testing was a modified version of a multi-shock shield. In order from the direction of the projectile trajectory is a layer of multi-layer insulation (MLI), three layers of Nextel spaced with a 35 mm standoff distance, a rear wall made of IM7/8552-1 graphite composite also at a 35 mm standoff, followed by a 2024-T3 Al witness plate placed 51 mm behind the composite (Fig. 1).

Results: All terrestrial analog projectiles, along the comparative, smaller Al sphere, were launched at 6.92±0.16 km s^{-1} and did not perforate the rear wall. The damage pattern to the composite rear wall, however, was observed to vary between the types of projectiles, which was further modified by the uncontrolled tilt at impact. In general, lower tilt angles (impactor trajectory in line with cylindrical axis) were associated with higher magnitudes of damage for cylindrical projectiles. Apart from tilt, the metal-bearing telluric iron produced the most significant damage to the rear wall, consisting of numerous small pit craters, the largest of which produced fiber stretching and bumps on the backside of the composite, which was absent from the test using dunite and basalt.

The meteorite sample and larger Al sphere were launched at 5.76±0.1 km s^{-1} and both resulted in shield failure, Fig. 2. Holes in the rear wall had similar areas between these two tests, but the meteorite projectile produced multiple pit craters around the main perforation, where the Al projectile produced more erosive damage around the perforation. The witness plate from the meteorite test exhibits numerous craters and evidence for a more substantial impulse load (a circular depression seen in Fig. 2E). A detailed analysis of damage and further testing will be presented.

References: [1] Christiansen, E. L., et al. (2009). 11th Hypervelocity Impact Symposium. [2] Schonberg, W. P. and J. M. Ratliff (2017). *Procedia engineering* 204. [3] Bird, J. M., et al. (1981). *JGR*: *Solid Earth* 86(B12). [4] Goodrich, C. A. and J. M. Bird (1985). *Journal. Of Geology* 93(4).

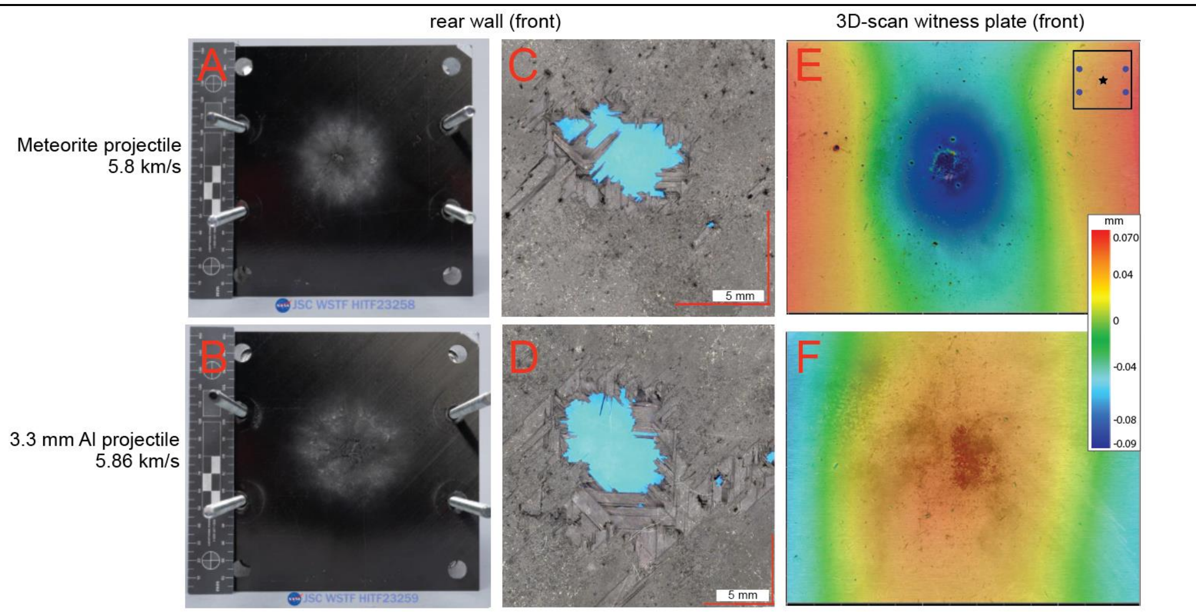

Figure 2. Damage on the (A and B) front of composite rear wall, with a (C and D) magnified view, and (E and F) 3D-scans of the witness plate from the meteorite projectile and comparative Al projectile tests. The apparent bending of the witness plates along the vertical axis is consequence of the mounting geometry that is shown in the upper right corner of panel E by the blue dots, with the impact point represented as a star.